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UTILITY OF A PROBABILITY DENSITY FUNCTION CURVE AND F-MAPS IN C--ETC(U)
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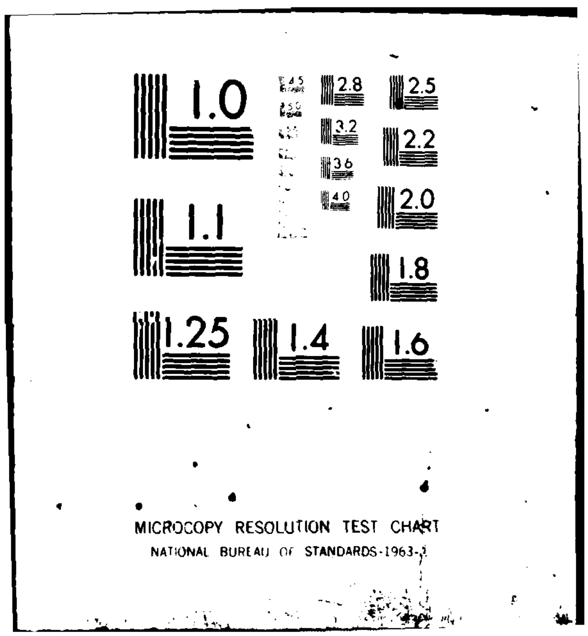
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(6) UTILITY OF A PROBABILITY DENSITY FUNCTION CURVE AND F-MAPS IN COMPOSITE MATERIAL INSPECTION*

by

(10) Joseph L. Rose

Yi H. Jeong

Michael J. Avioli

on

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ABSTRACT

The subject of probability density function analysis, an important topic in statistical analysis, is studied in detail in this paper for its utility in nondestructive testing. In addition to the mathematical concepts and analysis, several sample problems in composite material inspection are presented. An F-map, or feature map, presentation is also presented that gives us a new way to examine composite materials.

A probability density function basically gives us a plot of the number of times that a particular feature is recorded versus the feature value itself, a feature being defined as a specific item related to an ultrasonic waveform, possibly center frequency, attenuation at a particular frequency, etc. Probability density function curves are also used to set threshold values in producing an F-map. Sample problems in a graphite polyimide structure and a Boron Aluminum material are covered.

INTRODUCTION

The use of composite materials has increased rapidly in recent years, particularly in the aerospace and aircraft industries, due to such numerous advantages as high specific strength and modulus, dimensional stability, excellent fatigue resistance, light weight, etc.

Consequently, the efficient and reliable quality control of the products appeared to be one of the most important problems in those industries. But due to the complexity of the structure of composite materials, such as anisotropy, heterogeneity, multiple layering, and the presence of such flaws as cracking, porosity, resin rich and poor areas, and degradation, etc.; the establishment of efficient quality evaluation methods was very difficult.

Consequently, many nondestructive test methods have been used for the inspection of composite materials, including radiography, penetrants, holography, spectroscopy, acoustic emission, as well as ultrasonics. Most of those techniques, however, are still limited in the applicability to actual production line inspection because of limited experimental data. More practical and efficient test methods are therefore being developed for complete quality control in industry.

Some excellent research work has been carried out on the nondestructive testing of advanced composites. Reported by Hagemeier and Fassbender [1] and Martin [2] are some guidelines for inspecting composite materials. The usefulness of a variety of nondestructive testing methods is reviewed. With respect to ultrasonic testing, it is pointed out that C-scan procedures can be used for finding porosity, delamination, foreign objects, voids, and cracks. It is also mentioned that attenuation factors can be used to determine void content. Many of the concepts presented in references 1 and 2 can be extended to probability density function analysis and F-map utilization.

Probability density function analysis is introduced in this paper for solving a large number of engineering problems. A probability density function curve provides us with a plot of the number of times that a particular feature is observed versus the actual feature value. Of primary concern, probability density function curves can be used for feature evaluation in pattern recognition. In addition, many other applications in engineering, as well as quality control, are being considered. The principles of probability density function analysis are particularly suited to an inspection philosophy for composite materials. Possible applications include selection of manufacturing technology, quality control analysis, and damage assessment. These items are discussed in the paper. Sample problems in boron aluminum and graphite polyimide are included.

PDF THEORY, EXPECTATIONS, AND GENERATION

Mathematical details of probability density function analysis will be included in Appendix 1 of the final paper.

Curves expected for a composite material are illustrated in Figure 1. As indicated in Figure 1A, it is hoped that the distribution curve will be compact, indicating uniformity in the structural aspects of the composite material. Perfect fabrication, however, is not possible and that of a normal composite material, one suitable for use in the field, gives rise to a broader distribution as illustrated in Figure 1B. This distribution comes about because of variations in material properties and also in the fabrication procedures.

An inspectability parameter of a composite material can now be introduced and the hypotheses is simply that a more compact distribution curve leads to improved inspectability. The normal probability density function curve can be used in quality control and also in damage assessment. Therefore, if possible, it is suggested that a manufacturing procedure be based on inspectability so that quality control and damage assessment can be easier. Possible curves for a damaged composite material are shown in Figures 1C and 1D.

The probability density function curve can also be used to produce an F-scan of a composite structure, the F-scan being very useful in quantitative quality control and damage analysis. The procedure for producing an F-map is outlined in Figure 2. A comparison with a very popular C-scan procedure is also presented in Figure 2. The first block, transducer selection, is obviously a critical parameter. Both center frequency and frequency content must be specified. An automative or computerized scan is then carried out over the area of concern in a composite material. RF waveform data is then stored on a computer file, or in the case of some C-scan testing systems, run through a video signal analysis with proper gate setting and threshold selection. To produce a real time C-scan, the C-scan procedure is based on a gate selection at a specified depth and then a corresponding threshold criteria to produce a bistable display. In the case of an F-map routine, from which a C-scan could easily be produced, the RF data is then subjected to feature extraction and probability density function analysis. Thresholds can be selected from known probability density function distributions in order to assess certain kinds of damage in a composite structure. By software, an F-map can then be produced on a graphics terminal.

Sample problems that illustrate the application of probability density function curves and F-maps will now be presented in the next sections of the paper.

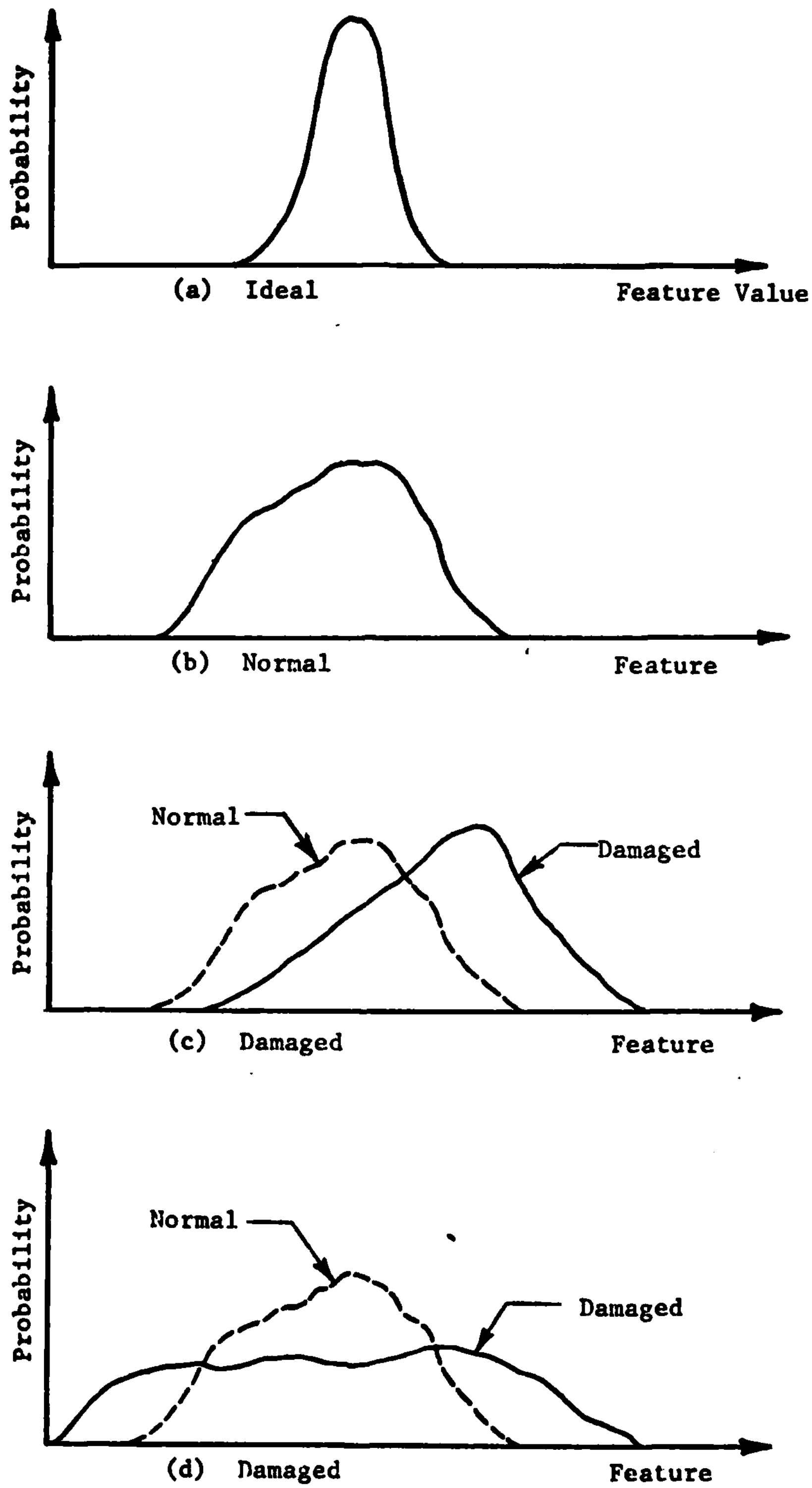


Figure 1. Typical Probability Density Function Curves for Composite Materials

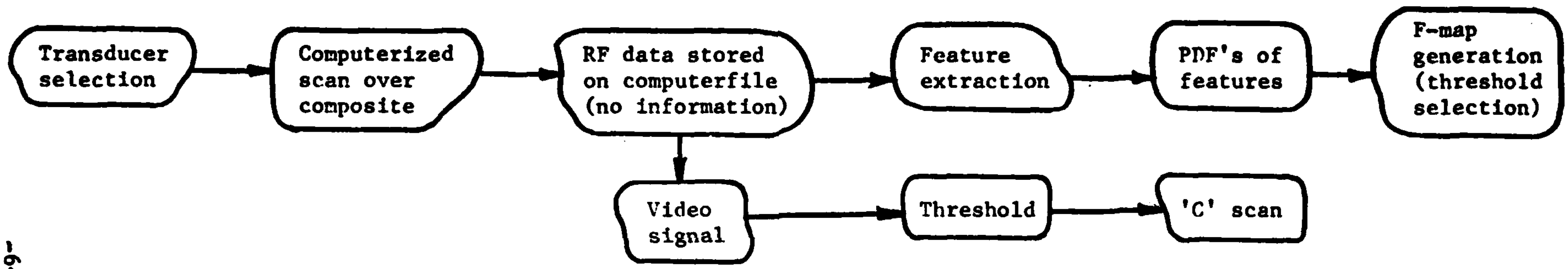


Figure 2. F-map Generation Procedure Compared with C-scan Analysis

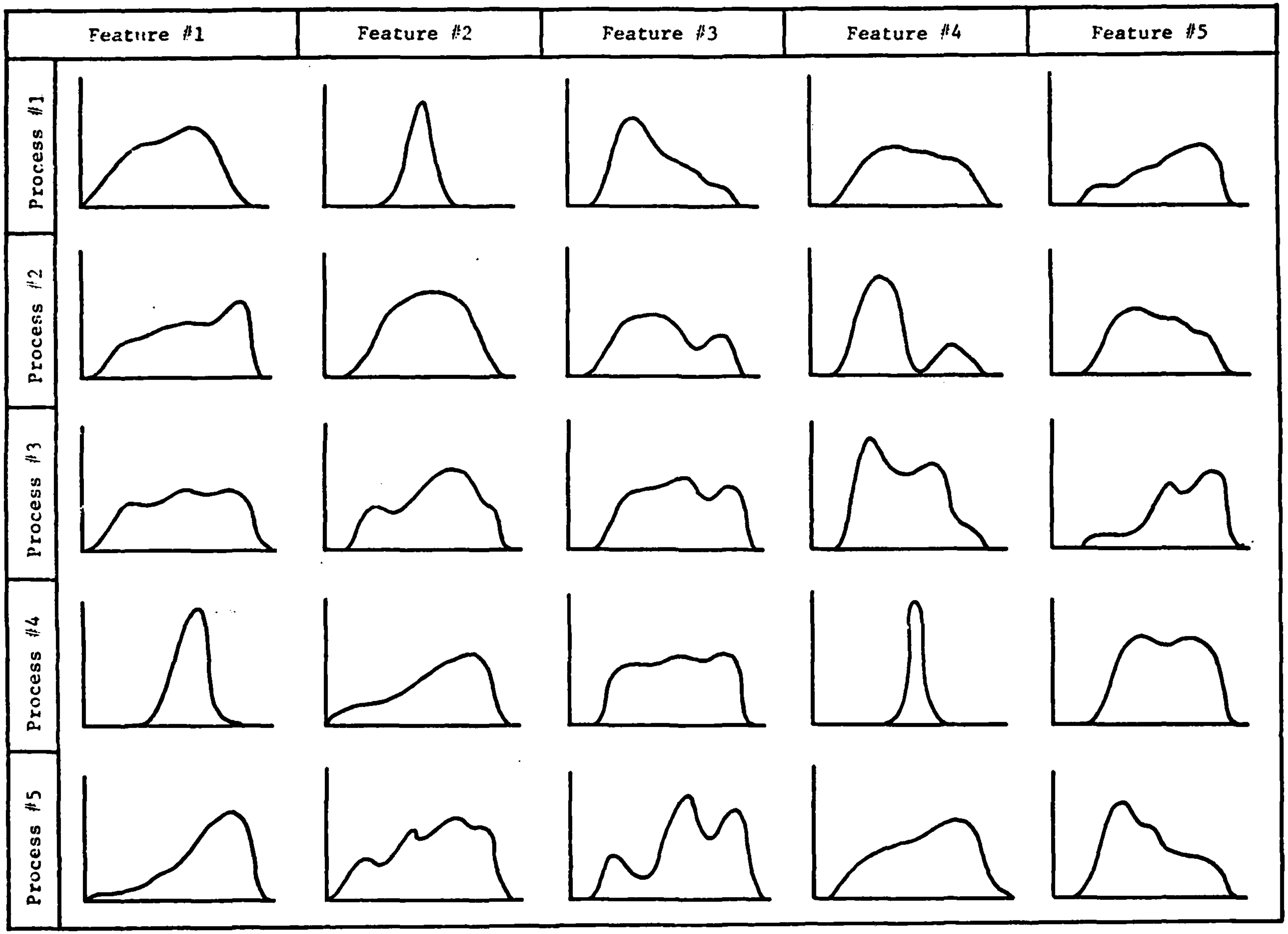
SELECTION OF MANUFACTURING TECHNOLOGY BASED ON INSPECTABILITY

It is proposed to add the parameter of inspectability to the already long existing list of such critical performance parameters as ultimate strength, fatigue life, fatigue life at high temperature, etc. in the selection process of a manufacturing technology for a new material system assuming that the critical strength and endurance parameters are the same. It is proposed to use inspectability as a key element in the selection process.

Let us assume that a composite material system could be fabricated by five different processes. In order to determine inspectability, a series of experiments should be conducted. Suppose that an analysis indicates that only five signal features are worthy of further analysis of an initial list of say n features. This hypothetical situation is illustrated in Figure 3. An analysis of the results in Figure 3 indicates that the most suitable manufacturing technology process would be either process #1 or process #4, this criteria associated with the compactness of the probability density function curve. In details of pattern recognition analysis process #4 might be best since both features #1 and #4 are excellent rather than just feature #2 in the first process.

Let us now consider a sample problem associated with the fabrication of boron aluminum metal matrix composite material. First of all, several boron aluminum manufacturing possibilities are listed below followed by a brief description of the kinds of flaws that could come about in a boron aluminum structure. The flaws are dependent on the fabrication technique, hence responsible for the establishment of a different probability density function for each manufacturing process.

Boron aluminum manufacturing possibilities are outlined below. Six different procedures are reviewed here.



x-axis; feature value
y-axis; probability

Figure 3. Hypothetical Selection of Manufacturing Technology Concepts Based on Inspectability and the Probability Density Function Curve

There were basically three processes used to fabricate the specimens used in the metal matrix study. Each of these processes were performed in two types of environments, air and vacuum, therefore six types of specimens were manufactured. The three processes are described below.

1. Plasma Spray - B fibres are located on an Al substrate and coated with a spray of Al. This forms one laminae. The final plate is formed by hot pressing eight layers together (hot pressing is a diffusion bond process).

2. Dry woven - Mats containing B fibers in one direction and Al fibers in another are made first. Then these mats are alternated with Al sheets. After the stacking procedure, the stack is hot pressed.

3. Monotape - Same as above, except that each laminae is hot pressed before stack hot pressing.

As noted above each process was performed in an air and in a vacuum environment giving us a total of six processes.

Associated with each of the manufacturing processes is a different quality level of manufacture. Possible flaws are outlined below.

a. Porosity or voids come about by less than a 100% dense material resulting from incomplete flow of the matrix in the bond process.

b. Aluminum plate bond line - oxide on the surface of the surface or intermediate aluminum sheets can prevent total bonding.

c. Fiber breakage

d. Variations in fiber volume or spacing

e. Matrix - fiber interaction - a chemical reaction can occur between the fiber and matrix material. This can be cured by coating the fiber. Since this is not apparently a problem with B/Al the boron is not coated.

f. Fiber or matrix oxidation - surface oxide can inhibit proper bonding. This may be more noticeable in those specimens hot pressed in air rather than a vacuum. The B fibers used in these panels were supposedly free of any initial oxide.

g. Matrix - fiber bonding - while it is expected that this bond will be good from an ultrasonic transmission standpoint, fiber pullout is commonly noted on fracture surfaces.

h. It should be noted that the B fibers are made by vapor deposition on a W wire. Thus each B fiber has a fine W core.

i. Warpage - in a unidirectional composite suggests either a misalignment of the fibers or a differential thermal expansion/contraction problem during the hot pressing procedure.

Curves similar to that shown in Figure 3 were then produced. A 10 MHz non-focused ultrasonic transducer was used on a variety of thin plate test specimens. Results of the study are shown in Figures 4A and 4B.

The dry woven air fabrication technique has a more compact PDF curve for the feature of center frequency, therefore giving it a better inspectability rating.

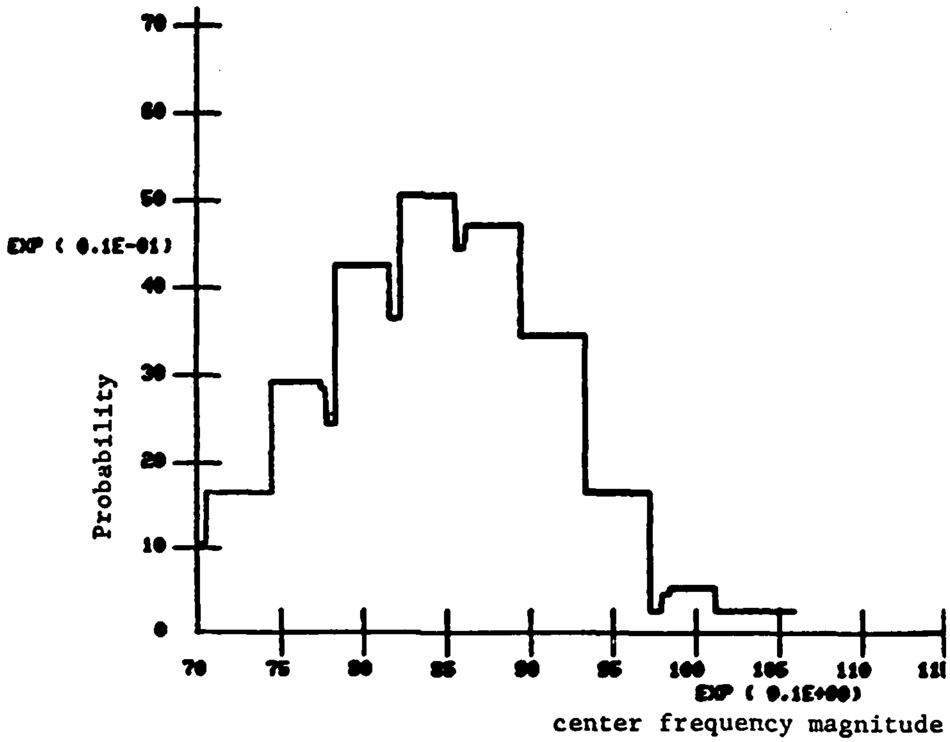


FIGURE 4A - PDF curve for a dry woven (air) boron aluminum fabrication process

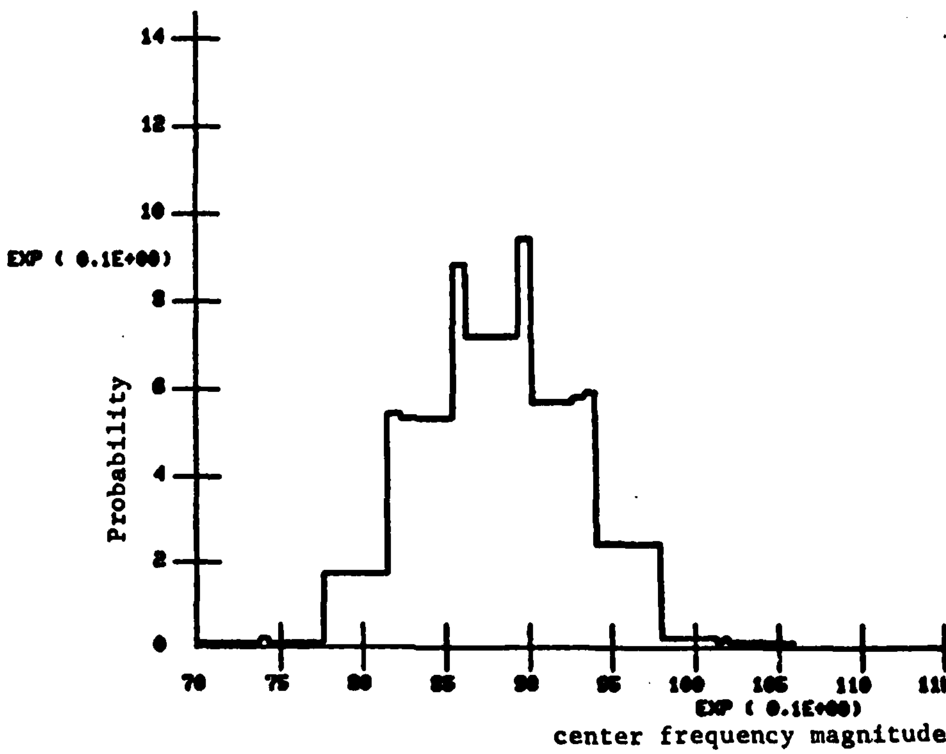
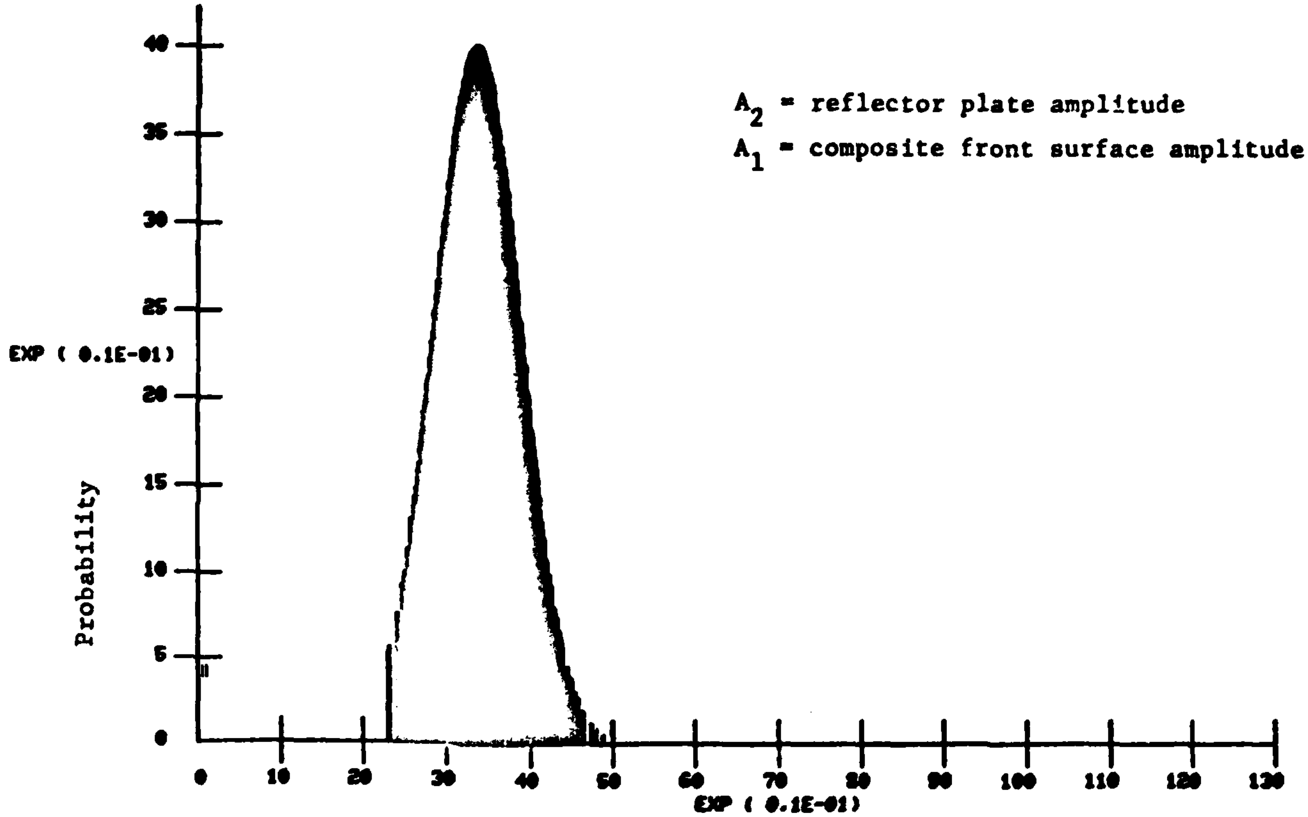


FIGURE 4B - PDF curve for a dry woven (vacuum) boron aluminum fabrication process

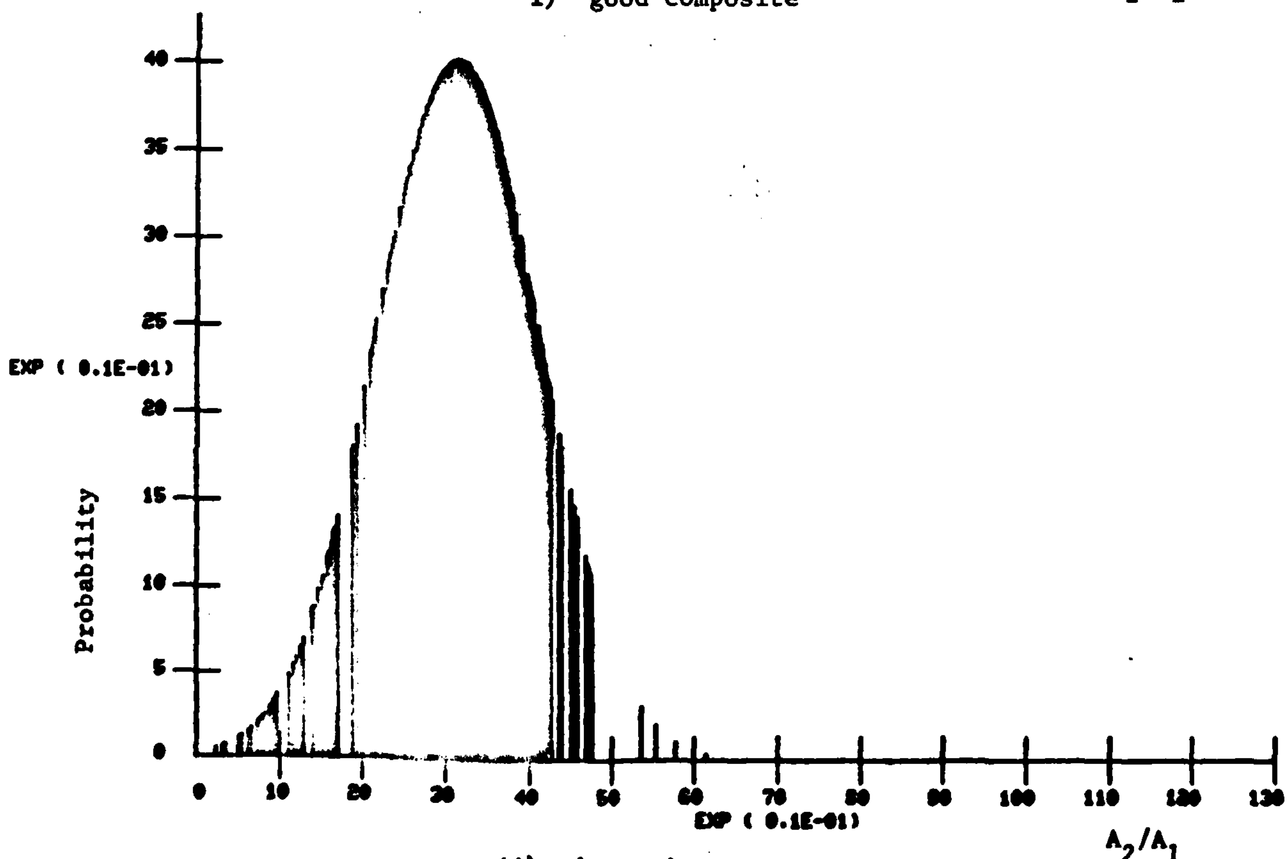
QUALITY CONTROL

Composite materials, because of the dual material contents, variation in fabrication, anisotropic character, etc., are noisy with respect to ultrasonic waveform content as reflected from the composite structure. A uniform composite material will have a probability density function curve for a particular feature that is fairly compact. Experimental analysis, of course, can acquire this PDF information or "PDF signature". Uniformity of composite materials can, therefore, be evaluated, since poorly manufactured composite materials would have a different PDF signature and most probably produce that of a wider and distorted PDF curve. A material acceptance criteria could, therefore, be written as a function of tolerances on the PDF curves.

Sample results for two graphite polyimide composite materials are shown in Figures 5 and 6. The concepts described earlier in the paper on the utilization of probability density function curves are used to produce F maps for a good and a bad composite structure. The PDF curves are used to obtain threshold values from which the F maps can be produced. A time domain feature was used in Figure 5. A reflector plate technique was used to acquire data from the fairly thin test specimens and the ratio of the reflector plate amplitude to the front surface input waveform was used. A frequency domain feature, that of a 6 dB down frequency bandwidth of the reflector plate echo was used in Figure 6. The results are self-explanatory. Potentially poor areas or damaged areas of the composite materials are clearly shown in the F maps. Some research must still be done, however, to describe the kinds of flaws that might be indicated in the F maps.

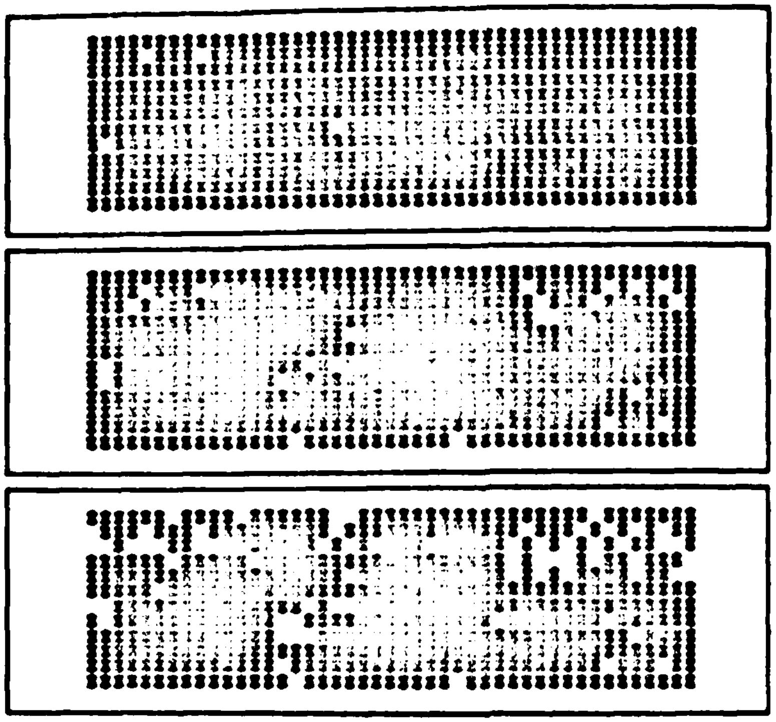


i) good composite



ii) damaged composite

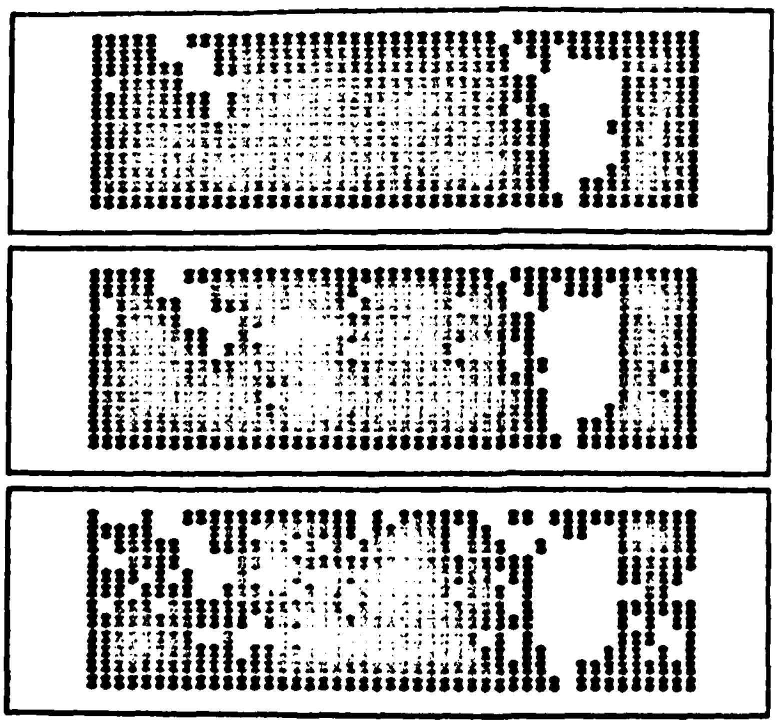
FIGURE 5A - PDF curves for two different graphite polyimide composite materials for the feature A_2/A_1



T = .24 critical damage

T = .26 intermediate damage

T = .28 minimal damage



T = .24 critical damage

T = .26 intermediate damage

T = .27 minimal damage

FIGURE 5B - F-maps of two different polyimide composites based on thresholds obtained from the PDF curves in figure 5A

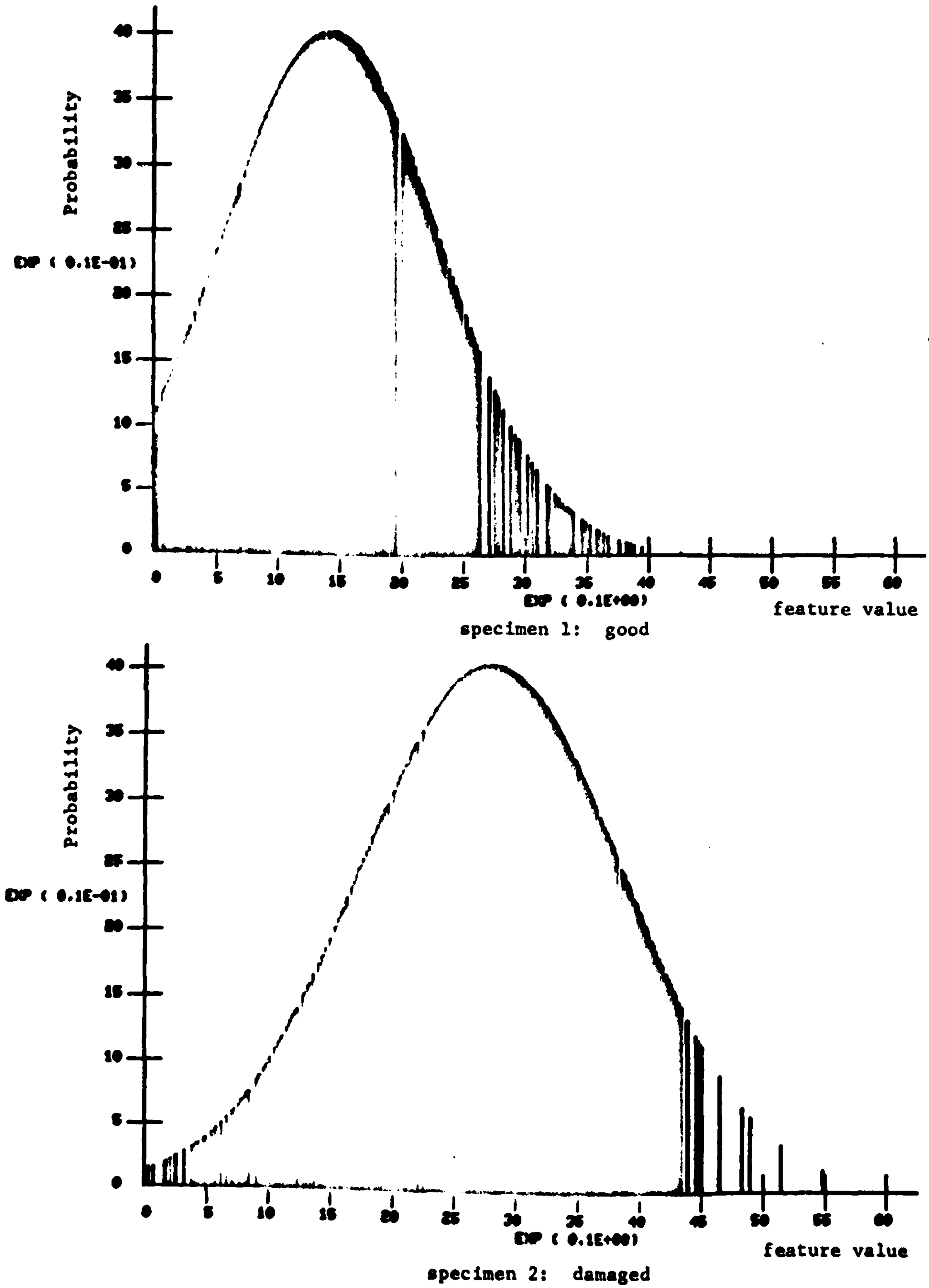
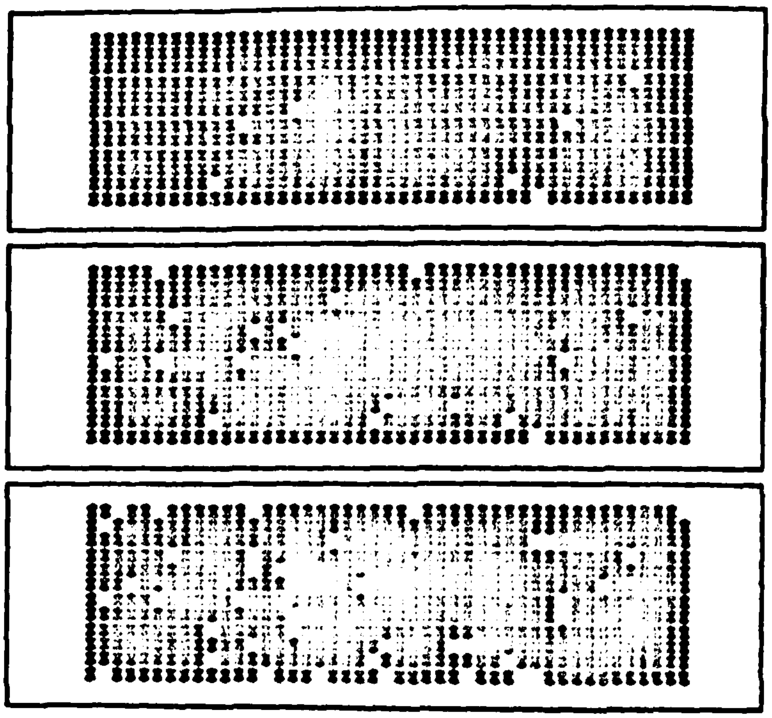


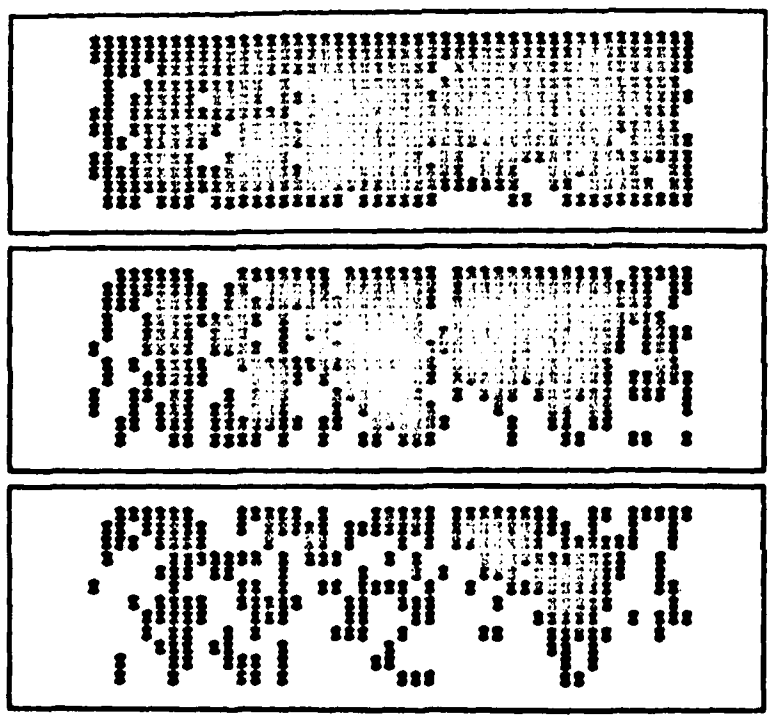
FIGURE 6A - PDF curves of two different graphite polyimide composites based on the feature of 6 dB frequency bandwidth



T = 4. critical damage

T = 3.5 intermediate damage

T = 3. minimal damage



T = 4. critical damage

T = 3.5 intermediate damage

T = 3. minimal damage

FIGURE 6B - F-maps of two different polyimide composites based on thresholds obtained from the PDF curves in figure 6A

DAMAGE ASSESSMENT

Once a PDF signature is acquired for a particular composite material, it is quite obvious that some marked change in a PDF curve is indicative of the material change or degradation. In most cases, the change would come about because of various defects such as crack, void, delamination, local volume variation (resin rich or poor areas), misaligned layup, etc. Because PDF curves can be produced at various areas of a composite material, they also can be used to get the damage propagation information. Sample results can easily be obtained. The results would be similar to those shown in Figures 5 and 6.

CONCLUDING REMARKS

1. Probability density function curves can be used to produce F-maps of a composite material, the F-maps being useful in both quality control and damage assessment. Much research remains, however, to point out the flaw types and their correlations with various F-maps.

2. C-scan test procedures are obviously useful but severely limited with respect to their ability in pointing out all damaged areas in a composite material. F-scan procedures can be used to study a greater variety of flaw types and not just a delamination in a composite structure.

3. Manufacturing technology selection should be based on inspectability as well as the more common performance characteristics of a composite materials, particularly when the performance of a composite material proves to be independent of its fabrication process. In most cases, inspectability can be related to the fabrication process.

4. Quality control tests based on a PDF signature could possibly be used to check material lay-ups and orientations, again either as a quality control tool or in fabrication selection based on inspectability.

5. Probability density function curves can even be used to select the transducers for material inspection. As an example, a comparison of single element versus dual element transducer application for a composite material can be evaluated. Dual element transducers might be better for the composite material inspection because of the removal of back scatter ultrasonic radiation. This physical principle of recording only forward scatter information can be demonstrated quite nicely by examining a number of features in a probability density function analysis. Nicely distributed and tight PDF curves can be used to select the best transducer for a particular application. A specific transducer frequency and bandwidth could be determined.

6. Many interesting things can be done with a dual threshold in F-map generation. The higher end of a PDF curve could indicate one quality control problem and the lower end another problem. This research tool could prove to be quite valuable in both quality control and damage assessment programs.

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